



A DIGITAL IMAGING DEVICE OPTIMIZED FOR COLOR
PERFORMANCE

FIELD OF THE INVENTION

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This invention pertains to the field of digital imaging and, more particularly, to the optimization of the color performance of digital imaging devices, such as digital cameras and scanners.

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BACKGROUND OF THE INVENTION

Correction matrices are useful in a variety of color imaging applications to effect color conversion or correction. For instance, a conversion matrix is used to convert red, green, and blue video signals into Y (luminance) and I, Q (chrominance) signals. A color correction matrix is used to correct the spectral sensitivities of a video camera for the chromaticities of the phosphor set of the particular display in use. Another use is with film-to-video conversion, a process in which a color correction matrix operates on the film scanning signals to correct the film colorimetry for video display. While these systems were typically analog systems, matrix processing is particularly adapted to a digital environment.

Continuing advances in semiconductor technology in areas such as digital memory, digital application-specific integrated circuits (ASICs) and charge-coupled device (CCD) imagers have made possible the introduction in recent years of digital electronic cameras. Evolution of this product segment will be driven by ever increasing consumer demands for better performance in such areas as resolution, photographic speed, and color reproduction. In the area of color reproduction it is desirable to select an optimum set

of spectral characteristics for the CCD imager. The prior art (for example, as described in Color Science in Television and Display Systems by W.N. Sproson, published by Adam Hilger Ltd, 1983), teaches that one
5 step toward the goal of good color reproduction is to choose a set of spectral characteristics for the camera which are as close as possible to the spectral characteristics of the intended display device. In the
10 aforementioned Sproson text, a color cathode-ray tube (CRT) is used as an example of a typical display device where the defining spectral characteristics are easily derived by someone skilled in the art from a knowledge of the CRT's phosphor chromaticities and white-point setting, as well as a knowledge of the spectral
15 response of the human eye. The resulting spectral curves are referred to as the color-matching functions (CMFs) for the display.

It is desirable to have the camera exhibit spectral sensitivities only in the visible portion of
20 electro-magnetic spectrum (approximately 400 to 700 nm.). In addition, it is desirable that the overall spectral sensitivities of the camera correspond to a set of all-positive color-matching-functions (CMFs). If these requirements are met, the camera will be able
25 to discern color information in the scene in much the same way that a human observer does. Failure to achieve this goal will result in color reproduction errors. (This failure mechanism is referred to as metamerism.)

30 A set of spectral curves is defined as a set of CMFs if, and only if, it can be exactly derived from the spectral response of the human eye via a linear 3x3 transformation. An infinite number of CMFs are possible according to this definition. The CIE
35 (Commission Internationale De L'Eclairage) has published standardized spectral data sets describing the response of the human eye. This data may be found

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in CIE publication 15.2 (1986) *Colorimetry - Second Edition* in table 2.5. Another useful feature of CMFs is the fact that any two sets of CMFs are directly related to each other through a unique 3x3 linear transformation.

One practical limitation in the selection of a set of CMFs for the camera is the restriction that they be all positive, whereas the CMFs describing a color CRT typically have negative lobes. This is not a problem in practice since a linear 3x3 transformation may be employed, as discussed above, to correct the camera's output color signals for rendition on the CRT display. This linear 3x3 transformation is often referred to in the art as a color-correction matrix.

Another practical restriction in the selection of a set of camera CMF's is the need to minimize the size of the off-diagonal coefficients in the color-correction matrix since these are directly responsible for degrading the noise performance of the imaging system.

The optical path of an electronic camera may consist of various components--each with its own spectral characteristics. Among these components one would ordinarily find a lens, blur-filter, infra-red cut-off filter and a CCD imager. The overall spectral sensitivity of the camera is determined by the combined spectral responses of the individual components.

Figure 1 illustrates the spectral characteristics for a typical color CCD camera including the combined effects of all of the optical components. These curves have been normalized to unit response for comparison purposes as is the standard practice when working with color-matching functions.

Included in Figure 1 is a second set (dotted lines) of curves representing the transformed spectral characteristics of the camera following the color-correction matrix operation. Note that the transformed spectral responses have negative lobes whereas the

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original camera spectral responses do not. Figure 2 compares the transformed spectral responses of the camera (dotted lines) with the CMFs for a CRT having CCIR Rec. 709 phosphors and a 6500 Kelvin white point.

5 It can be seen that elements in a real camera have errors in spectral response that prevent replication of CMFs regardless of the transformation. Errors are normally spread among all colors in a way that minimizes color errors, but the result inevitably is
10 not a perfect match, as seen particularly in the transformed camera red spectral response in Figure 2.

The use of a color-correction matrix is shown in U.S. Patent 5,253,047, in which a color temperature detecting circuit modifies the matrix coefficients for
15 a primary color separator used to perform a color-correction operation for a color video camera. The primary color separator is used to compute the red, green and blue primary color signals for the luminance/chrominance signals generated by the camera
20 detector circuitry. In U.S. Patent Application Serial No. 08/569,645, "Method and Apparatus for Color-Correcting Multi-channel Signals of a Digital Camera", filed December 8, 1995 to Spaulding et al, an improved method is used to select the color-correction matrix
25 coefficients to account for changes in illuminant color temperature. In particular, this method provides optimum compensation for variations in the scene illuminant by using all of the degrees-of-freedom available in the primary color separator matrix.

30 A color-correction matrix is shown in U.S. Patent No. 5,001,663 as one component of a digital-signal processing chipset for a high performance digital color video camera. The implementation illustrated requires that the matrix be mask-programmed
35 into the chip during fabrication. This approach fixes the matrix coefficients during the production process such that color correction is specific to a defined

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type, or family, of cameras. This is ordinarily done by establishing the matrix coefficients to account for the optical component spectral characteristic or illuminant color temperature of a defined reference camera, and then embodying these coefficients in each
5 manufactured camera.

U.S. Patent No. 5,189,511 is a further example of this approach, describing improved resolution and reproduction of hard copies made from
10 images captured by different types of electronic still cameras. Subtractive-type color processing is used to attempt to stabilize the primaries associated with image dyes used to produce the hard copy images, preceded by additive-type processing which attempts to
15 correct the camera sensitivities appropriately for the stabilized primaries. The additive-type color processing may be in the camera itself to ensure that each output device achieves optimum color reproduction from signals corresponding to those provided by a
20 defined reference camera. This arrangement allows signals from different types of cameras, i.e., corresponding to different defined reference cameras (e.g., high resolution professional cameras vs. low resolution consumer cameras), to provide input to
25 different types of hardcopy devices and media.

As digital cameras and low cost scanners proliferate in the marketplace, there is increased need that images from comparable cameras or scanners produce comparable colors to the human observer.
30 Unfortunately, small variations in optical component spectral characteristics, even within the same family of cameras, can produce noticeable color differences in the output images. Heretofore, the approaches taken do not account for variations in optical component
35 spectral characteristics from individual imaging device to individual imaging device.

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SUMMARY OF THE INVENTION

5 The aforementioned problems are solved with a
technique for optimum color correction utilizing
customized matrix coefficients for a particular imaging
device. According to the invention, a digital imaging
device captures an image and generates a color signal
from the image for application to an output device
10 having specific color sensitivities, the imaging device
further being one of many devices of the same type
useful with the output device. The digital imaging
device, for example a digital camera, includes a color
sensor for capturing the image and generating a color
15 signal from the captured image, the color sensor having
predetermined spectral sensitivities, and an optical
section that is interposed in the image light directed
to the color sensor, the optical section also having
predetermined spectral characteristics. Importantly,
20 the combination of the spectral sensitivities of the
color sensor and the spectral characteristics of the
optical section uniquely distinguish this particular
imaging device from other imaging devices of the same
type. By providing a set of matrix coefficients
25 uniquely determined for this imaging device, the matrix
coefficients optimally correct the spectral
sensitivities of the color sensor and the spectral
characteristics of the optical section for the color
sensitivities of the output device.

30 Besides providing an optimal level of color
correction, the present invention has the advantage
that the color reproduction variation from one camera
to the next is accordingly minimized. This reduces the
occurrence of color nonuniformity between the same
35 digital images captured by different digital cameras.

 These and other aspects, objects, features
and advantages of the present invention will be more

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clearly understood and appreciated from a review of the following detailed description of the preferred embodiments and appended claims, and by reference to the accompanying drawings.

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a comparison of the normalized original camera spectral characteristics and the
10 transformed spectral characteristics following application of a color-correction matrix.

FIG. 2 is a comparison of the transformed camera spectral characteristics from Figure 1 and the actual CMFs for a particular CRT.

15 FIG. 3 is a block diagram showing the preferred embodiment of the invention wherein the color matrix is located on the optical assembly of the camera, but the actual color-correction operation utilizing the matrix is performed external to the
20 camera.

FIG. 4 is a block diagram showing a second version of the preferred embodiment of the invention wherein the color matrix is located on the optical assembly of the camera and the color-correction
25 operation is performed internal to the camera.

FIG. 5 is a block diagram showing a third embodiment of the invention wherein the color matrix is located within the camera but external to the optical assembly of the camera.

30 FIG. 6 is a block diagram showing a fourth embodiment of the invention wherein the lens is removable from the camera.

FIG. 7 is a block diagram outlining a general method for obtaining the color-correction matrix
35 coefficients.

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FIG. 8 is a block diagram of an electronic imaging system incorporating an imaging device in accordance with the invention.

5 **DETAILED DESCRIPTION OF THE INVENTION**

Because electronic imaging devices employing electronic sensors are well known, the present description will be directed in particular to elements
10 forming part of, or cooperating more directly with, apparatus in accordance with the present invention. Elements not specifically shown or described herein may be selected from those known in the art. Certain aspects of the embodiments to be described may be
15 provided in software. Given the system description as described in the following materials, all such software implementation is conventional and within the ordinary skill in such arts.

As understood in the prior art, a digital
20 imaging device is a device which uses an electronic sensor to capture an image either directly from an object or indirectly from a medium, such as film; signal processing to represent the captured signal numerically; and some storage device to preserve the
25 numerical image data. It is further known for a digital imaging device, particularly a digital camera, to use a removable storage device, such as an integrated circuit memory card, to store images. For instance, U.S. Patent No. 5,016,107 describes an
30 electronic still camera utilizing image compression and providing digital storage in a removable memory card having a static random access memory. In this camera, the integrated circuits in the removable memory card store image data and a directory locating the data.
35 The image data provided by the digital imaging device and stored in a memory card is ordinarily used to produce some type of display or print, for example, a

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CRT display or a digital print made from images scanned from film or taken by an electronic camera.

As shown in Figure 8, the digital imaging device, which may be an electronic camera 10 or a scanner 11, is utilized in a system including a digital processor 12. The digital image information produced by the digital imaging device is downloaded to the peripheral digital processor 12, as shown in Figure 8, for further processing into a digital image. The downloading can be accomplished for either device in a number of ways, for instance by a cable connection 13 through an interface 14, or by removable media, such as a memory card 15, through a card reader 16. A suitable color CRT display 17 is connected to the digital processor 12 for displaying the images, and a printer 18 is connected to print out copies 18a of the images. A keyboard 19 is also connected for use in the processing of the images. The digital processor 12, which can be part of a conventional programmed computer, utilizes conventional processing techniques to process the digital image information according to algorithms stored in the computer or provided by application software used with the computer. For example, the digital processor 12 may include a conventional color management system, which links the input device (camera 10 or scanner 11) and the output device (CRT 17 or printer 18) by utilizing device profiles appropriate for the type of input and output devices used (e.g., one input profile for the camera 10 and another input profile for the scanner 11).

The ultimate color performance of an electronic camera is directly influenced by the various optical components which comprise the image capture path. It is possible to maximize the color reproduction accuracy of a particular camera by computing a unique color correction matrix for that camera which compensates for the unique optical

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characteristic of that camera. This approach also minimizes the variation in color reproduction from one camera to the next. With reference to Figure 3, a simplified block diagram illustrating the preferred embodiment of the invention is shown. The electronic camera 10 has an optical sub-assembly 20 containing a lens 22, an infrared cutoff filter 24, a blur filter 26 and a CCD imager 28 with an integral color filter array (CFA) 30. The optical subassembly 20 has predetermined spectral characteristics, comprising the combination of the spectral sensitivities of the CCD imager 28 and the spectral characteristics of the lens 22, the infrared cutoff filter 24, and the blur filter 26. Due to these spectral sensitivities and spectral characteristics, the combination thereof uniquely distinguish this imaging device from other imaging devices of the same type. In other words, although different cameras 10 contain nominally identical optical elements, including sensors, their overall spectral responses will differ from camera to camera.

The optical subassembly 20, which is used to capture an image of a scene 32, is designed to be removable from the camera 10 for purposes of servicing and calibration. When installed in the camera, the optical subassembly electrically connects to a preprocessing section 34 through an electrical connecting means 35. Image-wise signals $S_1 - S_N$ from the CCD imager 28 are converted to digital, linear RGB format within the camera by the pre-processing section 34 using techniques and components familiar to those skilled in the art. These digital RGB signals represent the red, green and blue primary components of the image, respectively. Pre-processing section 34 may perform such well-known tasks as double-correlated sampling of the CCD signals, black-level control, white-balance, analog-to-digital conversion, conversion

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of the CCD signals to RGB and interpolation of the CFA data to produce RGB values at each pixel location.

Digital RGB values from the pre-processing section 34 are transformed to a set of color-corrected
5 RGB values (R_{cc} , G_{cc} , B_{cc}) suitable for display on the color CRT display 17 by processing in a color matrix operation 40. In this embodiment of the invention, the color-correction matrix 40 operation is performed external to the camera as is shown in Figure 3 in, for
10 example, the digital processor 12 shown in Figure 8. Therefore, the RGB signals and the matrix coefficients are provided to the external digital processor 12 via interface lines 37a and b. In a second version of the preferred embodiment of this invention, the color-
15 correction matrix 40 operation is performed internal to the camera as illustrated in Figure 4. Where this step is performed is not important to the teaching of this invention. In either case the color-correction matrix 40 operation is performed on RGB signals which vary
20 linearly with exposure.

Color-corrected RGB signals (R_{cc} , G_{cc} , B_{cc}) following the color-correction matrix 40 operation are converted to a format suitable for CRT display by a post-processing section 50 using techniques and
25 components familiar to those skilled in the art. Such post processing operations may include such tasks as interpolation, edge-enhancement and tone-scale remapping, for example.

In the preferred embodiment of this invention as shown in Figure 3 and 4, the color-correction matrix coefficients for the color matrix operation 40 are stored in a digital memory 36 co-located on the optical sub-assembly 20 with all of the other optical components. These coefficients are uniquely determined
30 for each camera in order to correct the spectral sensitivities of the particular CCD imager 28 in the camera 10, and the spectral characteristics of the
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particular other elements in the optical subassembly 20, for the color sensitivities of the type of output device being used. (For this reason, while representing a specific imaging device, the

5 coefficients are ordinarily calculated in relation to a reference output device, rather than a specific individual output device.) These coefficients are then applied to the color matrix operation 40 for color

10 correction of the capture image. This approach has advantages in the production and service environments. In the production environment, optical sub-assemblies 20 can be fabricated, calibrated and stocked for later integration into the final product 10 without the need for calibrating the final product. In the service

15 environment, since the optical subassembly is replaceably interconnected to the preprocessing section 34 through the electrical connecting means 35, optical sub-assemblies 20 can be simply replaced without the need for calibrating the repaired product. Since each

20 optical subassembly 20 is calibrated for the particular optical components on the subassembly, it may be appreciated that the matrix coefficients stored in the memory 36 are unique for each subassembly 20, and therefore for each camera 10.

25 Note that, although RGB signals have been discussed by way of example as the tristimulus format of choice for representing the scene color information, this invention is not restricted to use with this format alone. Other tristimulus formats such as the

30 CIE XYZ format are equally applicable and may, in fact, present advantages in a particular implementation. Since the CIE XYZ format is a device independent space based on a set of CMFs defined by the CIE 1931 Standard Colorimetric Observer (2°), the matrix coefficients

35 could be used to generate an input profile unique to each camera which will correct the spectral sensitivities of the camera for the standardized CMFs

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of this device independent space. For example, in one application following the ICC Profile Format Specification (Version 3.2, November 20, 1995, published by the International Color Consortium), RGB
5 input profiles are established which will correct the spectral sensitivities of an input device for a connection space. Thereupon, output profiles are used to convert the signals from the connection space to a format that is expected by an output device. It should
10 therefore be understood that this invention encompasses linear tristimulus formats in general while the discussion is limited to the familiar RGB format for ease of understanding.

Figure 5 illustrates a third embodiment of
15 the invention wherein the color-correction matrix coefficients for the matrix operation 40 are stored in a digital memory 38 located somewhere within the camera 10 but not necessarily on the optical sub-assembly 20. In this embodiment, the aforementioned advantages in
20 the production and service environments are not realizable but the color reproduction accuracy and consistency goals of the invention are not compromised.

Figure 6 illustrates a fourth embodiment of the invention wherein the lens 22 is not physically
25 part of the optical sub-assembly and may, in fact, be removable as is the case of a camera with interchangeable lenses. In this situation the camera or optical sub-assembly, depending on where the color-coefficient matrix digital memory 38 is located, is
30 calibrated using a lens with a spectral response representing the average of the spectral responses of all lenses that are anticipated to be used with the camera. This represents only a slight compromise since the lens does not contribute significantly to
35 variations in color reproduction performance.

The present invention has been described thus far with regard to a series of preferred embodiments

outlining the location of the color-correction matrix coefficients within the camera as well as their application in the image processing path. Figure 7 illustrates a general method for obtaining these

5 coefficients. A color chart 72 containing colors representative of the expected range of real world colors provides the basis for the coefficients calculation process. An example of such a chart is the well known Macbeth Color Checker.

10 A necessary first step involves measurement of the spectral characteristic (S_λ) of the illuminant 74 as well as measurement of the spectral characteristic ($R_{i\lambda}$) of each color patch of the color chart 72. CIE tristimulus values (XYZ), describing the

15 location of a particular color patch in the 3-dimensional XYZ color space, may then be computed from the measured spectral data as described in the aforementioned CIE publication 15.2 (1986) *Colorimetry--Second Edition* on pages 22-23. This set

20 of XYZ values becomes the colorimetric aims for the camera.

The electronic camera 10 is used to capture an image of the color chart 72 under the specified illuminant 74. RGB camera signals representative of

25 the captured color chart image are next subjected to a normalization process 78 to provide RGB signals which vary linearly with scene luminance. The normalization process 78 may include removal of the camera gamma/knee characteristic as well as black-level, white-balance

30 and exposure errors.

Linear RGB signals are transformed to a set of color-corrected RGB signals by color-correction matrix transformation 79. Initially this matrix is set equal to the identity matrix. The coefficients are

35 subsequently adjusted in an iterative fashion by a regression process 80 until the average color error for

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all color patches of the color chart 72 is reduced to a predetermined level.

Color-corrected RGB signals from color-correction matrix transformation 79 are retransformed to a set of CIE XYZ signals by CRT phosphor matrix transformation 84. These signals represent the colors which would appear on the face of a reference CRT when presented with the color-corrected RGB signals from color-correction matrix transformation 79. It would be understood by someone skilled in the art that these color-corrected signals would first need to be modified to account for the nonlinear characteristic of the CRT phosphors. The resulting XYZ signals from CRT phosphor transformation matrix 84 represent the reproduced colors for each color patch of the color chart 72 for a reference output device, in this case the reference CRT.

An error calculation process 82 determines the average error between the aim and reproduction signals for all of the color patches on the color chart 72. An individual color error is first computed for each color patch using the square-root of the sum of the squares of the differences of the aim and reproduction X, Y and Z signals. This represents the vector length between the location of the aim and reproduction colors in the 3-dimensional XYZ color space. The last part of the error calculation is to average the individual color errors. This average color error is used in the regression process 80.

The foregoing matrix coefficient calculation process has been described from the standpoint of obtaining a good colorimetric match between the original scene and its reproduction on a CRT. For some applications this may not be the desired color reproduction goal. Modifications to the method shown in Figure 7 may be made to achieve a preferred color reproduction goal by taking into account such factors

as chromatic adaptation and more perceptually uniform color spaces.

- The invention has been described with reference to a preferred embodiment. However, it will
- 5 be appreciated that variations and modifications can be effected by a person of ordinary skill in the art without departing from the scope of the invention.

PARTS LIST

- 10 Electronic camera
- 11 Electronic scanner
- 12 Image processing external to camera (peripheral
digital processor)
- 13 Interface cable
- 14 Digital interface
- 15 Memory card, removable
- 16 Card reader
- 17 Color CRT display
- 18 Printer, color
- 18a Color print
- 19 Keyboard
- 20 Optical sub-assembly
- 22 Lens
- 24 Infra-red cutoff filter
- 26 Blur filter
- 28 CCD Imager
- 30 Color filter array (CFA)
- 32 Scene
- 34 Camera video pre-processing section
- 36 Color-correction matrix coefficient memory on
optical subassembly
- 38 Color-correction matrix coefficient memory in
camera
- 40 Color-correction matrix transformation
- 50 Post-processing section

- 72 Color chart
- 74 Illuminant
- 76 XYZ calculation process
- 78 Normalization process
- 79 Color-correction matrix transformation
- 80 Regression process
- 82 Color error calculation process

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